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NACA

RESEARCH MEMORANDUM

LONGITUDINAL CHARACTERISTICS OF WINGS

By Thomas A. Toll

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NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS
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INTRODUCTION

Recent information relative to the drag at zero lift and the variation of drag within the lower range of lift coefficients is summarized in references 1 to 3. In considering the complete range of lift coefficients for normal flight operations, the performance characteristics and longitudinal stability are perhaps equally important factors in the selection of the wing configuration. One objective of the designer can be regarded as the achievement of the best possible compromise between performance and stability over the ranges of Mach number and lift coefficient that are likely to be encountered. This paper deals with various approaches toward realization of this objective in so far as the wing or wing-fuselage characteristics are concerned. Consideration is given only to wings of 6-percent thickness or less.

SYMBOLS

A	wing aspect ratio
C_L	lift coefficient
C_m	pitching-moment coefficient
L/D	lift-drag ratio
M	Mach number
R	Reynolds number
b	wing span
c	local wing chord
$\bar{c}$	mean aerodynamic chord
r	wing section leading-edge radius

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t maximum thickness of wing section

x_{ac} distance measured rearward from leading edge of wing mean aerodynamic chord to wing aerodynamic center

Δx_{ac} shift in longitudinal position of wing aerodynamic center at low lift

Δx_{cp} change in longitudinal position of wing center of pressure

Δy_{cp} change in lateral position of wing center of pressure

λ wing taper ratio; ratio of tip chord to root chord

$\Lambda_{c/4}$ wing sweep angle measured with respect to quarter-chord line

Λ_{LE} wing sweep angle measured with respect to leading edge

δ_n deflection of leading-edge flap, measured in plane parallel to plane of symmetry, positive when leading edge is down

RESULTS AND DISCUSSION

Wing Plan Forms

Wing plan forms which are representative of those in which interest has been centered are shown in figure 1. The three wings at the left have attracted considerable interest because of their attractive performance capabilities. In general, these wings require some modification or "fix" if satisfactory high-lift stability is to be attained. The three composite wings shown at the center represent an approach toward achieving good stability while maintaining the benefits of a moderately high aspect ratio and at least some of the benefits resulting from large sweep. The wings at the right represent plan forms that might be expected to avoid high-lift stability problems through use of small sweep angles.

Wings of Large Sweep

Basic characteristics.- The nature of the stability problem that exists for wings of the type shown at the left of figure 1 is illustrated in figure 2. Results for several such wings are published in references 4 to 11. The wing geometry and Reynolds numbers are given at the right of

the figure. Each of these wings shows some pitching-moment instability within the normal operating lift range. Although the magnitude of the instability and the lift coefficient at which the instability begins vary somewhat for the different wings, the most severe condition exists at a Mach number of about 0.9 for each of these wings. At a Mach number of 1.0 the stability problem is essentially eliminated for two of the wings and is alleviated somewhat for the third. At supersonic speeds higher than those considered in figure 2, the wing-fuselage normally does not present a major stability problem. Of the plan forms shown in this figure, wings having about the aspect ratio and sweep angle of the wing at the top have received the greatest amount of attention with regard to means for improving their behavior. The objective in the studies that have been made is not necessarily the achievement of linear pitching-moment characteristics of the wing-fuselage combination, since, when a tail is used, the additional contribution of a tail generally is not linear. It is desirable however to avoid abrupt changes in slope such as those shown in figure 2.

Before considering the effects of variations in the geometry of the wing shown at the top of figure 2, it is appropriate to study the manner in which aerodynamic characteristics are altered through application of the area-rule concept in the design of the fuselage. The pitching moments and lift-drag ratios obtained at Mach numbers of 0.9 and 1.0 for the wing mounted on a cylindrical fuselage and on the fuselage modified by an indentation in accordance with the area-rule concept are presented in figure 3. (For additional details, see refs. 5 and 12). The results at $M = 0.9$ are representative of conditions in the subsonic speed range where the indentation has little effect on the lift-drag ratio. The results at a Mach number of 1.0 represent a transonic condition for which the indentation provides an appreciable gain in lift-drag ratios. At either Mach number, the effect of the indentation on pitching moments is small and amounts primarily to a slight extension of the lift range before instability begins. Indentations applied to some other wing-fuselage configurations have provided considerably larger performance gains than that indicated here; however, the effect on stability still was small.

It should be pointed out that the lift-drag ratios presented in the various figures contained herein should be interpreted only with respect to the variables considered on a given figure, since the investigations to be summarized employed different fuselage shapes and also differed in certain other details.

In considering wings of the aspect ratio and sweep angle shown in figure 3, the question arises as to whether benefits can be derived by selecting some taper ratio different from the value of 0.6 used. Figure 4 presents results from reference 11 at Mach numbers of 0.8 and 0.91 for wings having taper ratios varying from 0.3 to 1.0. The assumed centers of gravity for these wings have been adjusted to give the same slope of the moment curves for all wings near zero lift and at low Mach numbers.

The moment curves show that high-lift instability occurs for all wings, but that there is a progressive increase in the lift coefficient at which instability begins as the taper ratio is increased from 0.3 to 1.0. Essentially no change in the lift-drag ratios is indicated for these wings over the range of taper ratios considered. These wings, however, all were of 6-percent thickness. Since the taper-ratio-0.3 wing would seem to be the most efficient structure, its thickness probably could be reduced somewhat and some performance advantage thereby achieved at transonic and supersonic speeds. This wing was selected as the basic plan form for an extensive study of various modifications.

Modifications to swept wings.- The effect of a variation in leading-edge radius is compared in figure 5 with the effect of 6° droop of a 20-percent-chord leading-edge flap. The point symbols give results for a sharp nose, for the normal nose of the basic 65A006 airfoil, and for a nose having three times the radius of the nose of the basic airfoil. The solid-line curves were obtained from reference 13 and represent results obtained with the nose flap deflected 6° on the basic wing. At the selected Mach numbers of 0.8 and 0.9 the variation in leading-edge radius had no significant effect on either the stability or the lift-drag ratios of this wing. Deflection of the leading-edge flap improved the lift-drag ratios and extended the linear range of the pitching-moment curves. The advantage of droop was smaller at the higher Mach number. Some limited tests at transonic speeds (refs. 14 to 16) and at supersonic speeds have indicated that only a very small advantage can be expected by deflecting a leading-edge flap on a wing of the type used here.

The effects of leading-edge droop indicated in figure 5 also are representative of effects resulting from camber, camber and twist (refs. 17 and 18), and large-span slats. In general, such modifications improve the drag characteristics and extend the linear range of the pitching-moment curves but do not alleviate the instability at high lift.

More significant effects on stability at high lift have been obtained by such devices as fences, leading-edge chord-extensions, and notches in the wing leading edge. (See refs. 7, 8, and 13.) About the same effect has been indicated (ref. 19) for external stores if they are carefully positioned along the wing span. Each of these devices appears to depend largely on an ability to upset the stability of the leading-edge vortex that frequently exists on thin swept wings at moderately high angles of attack. Any change in flow phenomena that destroys the vortex will greatly decrease the effectiveness of these devices. The effects of these devices on pitching moments result largely from controlling the location at which stalling is initiated and not through any appreciable reduction in the amount of separation. As would be expected, therefore, such devices have little effect on drag characteristics.

It has been shown in references 13 and 14 that combining a leading-edge chord-extension with a full-span drooped nose flap permits both the performance benefit of the nose flap and the stability advantage of the chord-extension to be obtained simultaneously. The effects of this combination and of some additional modifications are shown in figure 6. The results for the basic wing are given by the solid curves. Results for the chord-extension combined with the deflected nose flap are given by the short-dashed curves. Note the rather large gains in both stability and lift-drag ratios that are obtained. The additional modifications consisted of a wing cutout with refairing of the wing contour near the fuselage intersection and a trailing-edge extension. These additional modifications provided some additional control over the pitching-moments at high lift but did not provide completely satisfactory stability at the selected Mach numbers of 0.8 and 0.9. It is a point of interest that a modification opposite to the wing cutout shown here - that is, a forward extension of the wing chord near the fuselage - has been found to aggravate the high-lift stability problem (ref. 20, for example). A comparison of the lift-drag ratios of the latter two modifications with those obtained with only the nose flap and chord-extension shows that the trailing-edge extension sometimes gave some improvement, but the leading-edge cutout had an adverse effect. All three modifications provided improvements over results obtained with the basic wing.

Composite wings.- A more extreme method of handling the stability problem involves use of composite wing plan forms. In figure 7 results for an M-wing, a W-wing, and a plan form sometimes referred to as a "cranked wing" are compared with results for the basic 45° swept wing from which the composite plan forms were derived. In order to facilitate the comparison, the pitching-moment curves for all wings were adjusted to the same slope near zero lift at Mach number 0.8. The results indicate that the M-wing at least offers an effective means for controlling high-lift stability in the critical Mach number range near 0.9. Selection of different juncture locations or different sweep angles of the inboard and outboard panels should make it possible to achieve additional improvements in the shapes of the pitching-moment curves. It must be emphasized, however, that the more favorable stability characteristics obtained with these plan forms again result from controlling the locations at which flow separation is initiated and not from any material decrease in the amount of separation. Tuft surveys indicate separation at the root and tips of the M-wing and at the panel junctures for the W and cranked wings. At the selected Mach numbers of 0.8 and 0.9 the lift-drag ratios for the M-wing compare favorably with those of the basic swept wing. It is not known, however, to what extent the characteristics of the composite wings might be improved by such devices as nose flaps or camber. Some minimum drag penalty has been indicated for M- and W-wings at transonic speeds; however, no penalty has been noted above a Mach number of about 1.25. (See ref. 21.)

Modifications to triangular wings.- Experience in applying modifications to triangular wings so far has been quite limited. The effects of one modification – a leading-edge chord-extension – are shown in figure 8. The characteristics of the basic model without chord-extensions are given at Mach numbers of 0.85 and 0.95 by the solid-line curves. The instability which covered only a small lift-coefficient range was essentially eliminated by the chord-extensions (dashed curves). The results shown here are representative of the entire Mach number range for which instability of the basic model existed. In this case the effect of the fix might be regarded as being complete; however for some other triangular-wing models having different fuselage configurations, this type of fix did not completely eliminate the instability. The effect of the modification on lift-drag ratios generally has been found to be insignificant, as is indicated in this figure. It has not yet been clearly established whether the stability advantages of modifications such as the chord-extension and the performance advantage of a cambered leading edge can be obtained simultaneously by combining the two devices.

Wings of Small Sweep

Considerations regarding use of small sweep.- In considering the possible use of straight wings or wings of reduced sweep as a means of avoiding stability difficulties, the possibility of a penalty in performance is of course of paramount interest. Whether such a penalty exists can be determined only as a result of detailed design studies with consideration given to aerodynamic data of the type discussed in references 22 to 27.

Another factor that needs careful consideration is the magnitude of the shift in aerodynamic center of these wings while passing from subsonic to supersonic speeds. An attempt to correlate this shift for thin wings in the region of zero lift is indicated in figure 9. The incremental change in aerodynamic-center position (defined as the difference between maximum forward and maximum rearward aerodynamic-center positions below a Mach number of 1.15) is plotted against sweep angle. Results are considered for aspect ratios of 2, 3, 3.5, and 4. Wings having values of the taper ratio parameter λ less than 0.4 are indicated by open symbols and wings with λ greater than 0.4 are indicated by solid symbols. For the range of plan forms considered, there appeared to be very little correlation with aspect ratio and, in general, little correlation with taper ratio; although for small sweep angles there is an indication of a larger aerodynamic-center shift for the larger taper ratios. A fairly definite trend with sweep angle results and indicates an increase in the aerodynamic-center shift by about 6 percent of the chord as the sweep angle is reduced from 45° to 0°.

Straight wings.- The stability characteristics of two straight wings are shown in figure 10. The results for the aspect-ratio-4 wing shown at the top were obtained in the Langley 16-foot transonic tunnel at a Reynolds number of 6×10^6. Results given in the bottom plot are for an aspect-ratio-3 wing tested in the Ames 2- by 2-foot transonic tunnel at a Reynolds number of 1.5 million. The characteristics of these wings are generally similar. Nonlinearities again appear in the pitching-moment curves, particularly at Mach number 0.9. In these cases, however, difficulties may result from excessive stability, rather than from a loss in stability, at high lift. As was indicated for the other wings, a final evaluation depends on the stability characteristics that are obtainable with the horizontal tail installed.

Selection of Sweep Angle.- With regard to the wing contribution to stability, it would be desirable to indicate some quantitative relation between pitching-moment nonlinearities – whether they are stabilizing or destabilizing – and the wing geometry. Results of an attempt to form such a relation are indicated on figures 11 and 12. The analysis has been made in terms of the center-of-pressure change with increasing lift. Evaluations of this change were made by subtracting center-of-pressure locations at low lift from the center-of-pressure locations at a lift coefficient of 0.6 and at the maximum lift coefficient. Results from a systematic series of wings tested on a transonic bump through maximum lift and to Mach numbers of about 1.2 at a Reynolds number of 1.0×10^6 were used in the analysis. The six wings considered on figure 11 had a taper ratio of 0, an aspect ratio of 4.0, and sweep angles varying from -14° to 45°. Figure 12 gives results obtained with the same wings, but with the tips clipped to give an aspect ratio of 3 and a taper ratio of 0.14.

Since the wings were tested as reflection-plane models, both the longitudinal change $\left(\frac{\Delta x_{cp}}{\bar{c}}\right)$ and the lateral change $\left(\frac{\Delta y_{cp}}{b/2}\right)$ in center of pressure could be determined. The results show that, in general, the longitudinal center-of-pressure changes at a Mach number of 1.1 were considerably smaller than the changes at a Mach number of 0.9. Fairly large lateral changes occurred at both Mach numbers, however. Whether a rearward or a forward change in wing center of pressure is desired for a particular design will depend on factors not dealt with in this paper; however, for purposes of illustration, it is of interest to consider the case for which a minimum change in longitudinal position of the center of pressure is desired. For the pointed wings of aspect ratio 4, a sweep angle in the vicinity of 20° or 30° would be selected to meet this requirement. For the clipped wings of aspect ratio 3, a sweep angle between 30° and 40° is indicated. It is important to note that for either wing series, the wings that would be expected to give the smallest longitudinal changes in center of pressure would experience appreciable inward changes in center of pressure at a Mach number of 0.9,

even at the relatively low lift coefficient of 0.6. Such inward displacements are associated with tip stalling and a reduction in the effective span of the trailing vortex sheet. This may cause erratic changes in downwash as well as buffeting and erratic changes in the lateral stability derivatives.

Wings of intermediate sweep.- The charts of figures 11 and 12 are of limited use for general design purposes in that they deal with only two specific series of wings; also, the test Reynolds number was only 1.0×10^6. It should be of interest to inspect the stability characteristics of two wings tested at higher Reynolds number but having aspect ratios and sweep angles such that small changes in center of pressure would be expected. The results are given in figure 13. Both wings are of aspect ratio 3. One wing, having 37° sweep and a taper ratio of 0.2, conforms closely to the conditions for minimum change in center of pressure indicated by figure 12. The other wing, because of its smaller sweep angle, would be expected to experience some increase in stability at high lift. Results for both wings show some jogs in the pitching-moment curves, particularly at Mach numbers near 0.9. In general, however, the nonlinearities are smaller than those indicated for most of the wings discussed previously, and the major trends are about as would be expected from the preceding charts.

CONCLUDING REMARKS

In summary, this paper has treated three approaches to the problem of wing selection. The first involves use of modifications or "fixes" to correct the basic instability of wings with relatively large sweep angles. Such modifications, if carefully tailored to the wing being considered, may provide marked improvements in both stability and performance at the lower subsonic Mach numbers; however, in general, there is no assurance that the modifications will be sufficiently effective, particularly at Mach numbers near 0.9. The other two approaches involve use of composite wings – particularly the M-type plan form – or wings of intermediate sweep. These latter methods provide a more positive means of dealing with the stability problem. The methods considered do not necessarily provide alleviation of flow separation at high lift, and therefore problems involving buffeting, erratic downwash, and erratic lateral-stability derivatives may exist even though the static longitudinal stability of the wing-fuselage combination is apparently good.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., September 3, 1953.

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WING PLAN FORMS

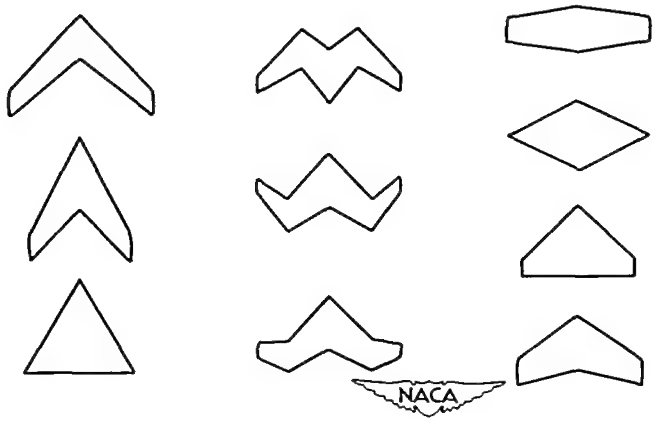

Figure 1

PITCHING MOMENTS — LARGE SWEEP

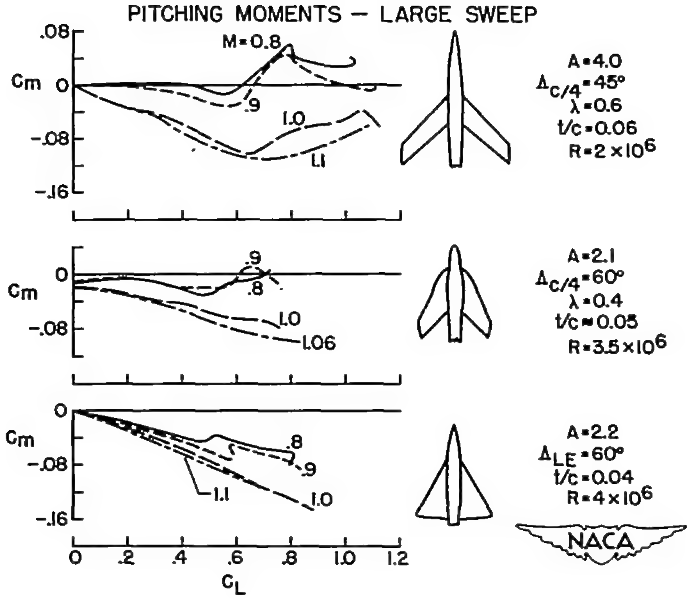

Figure 2

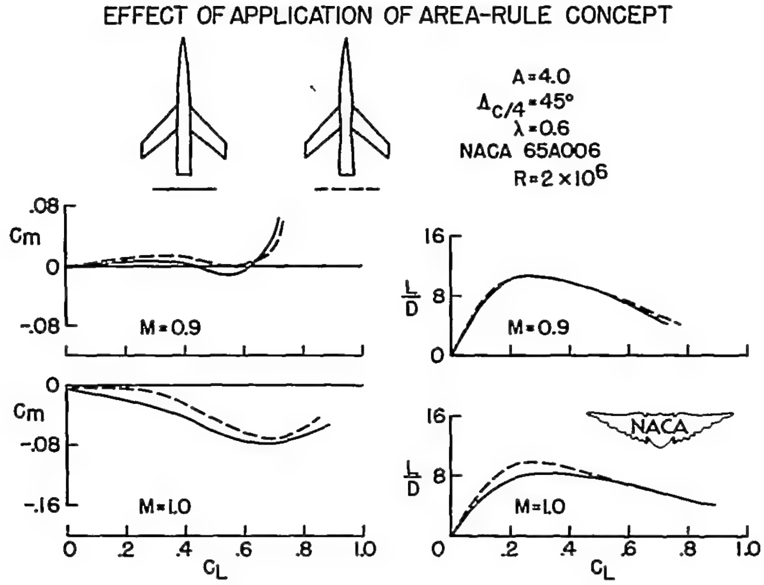

Figure 3

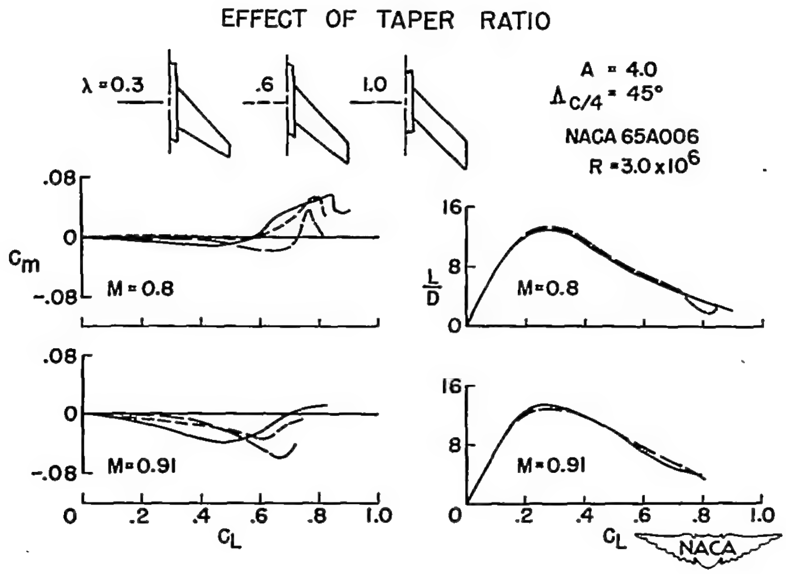

Figure 4

EFFECT OF NOSE RADIUS AND DROOP

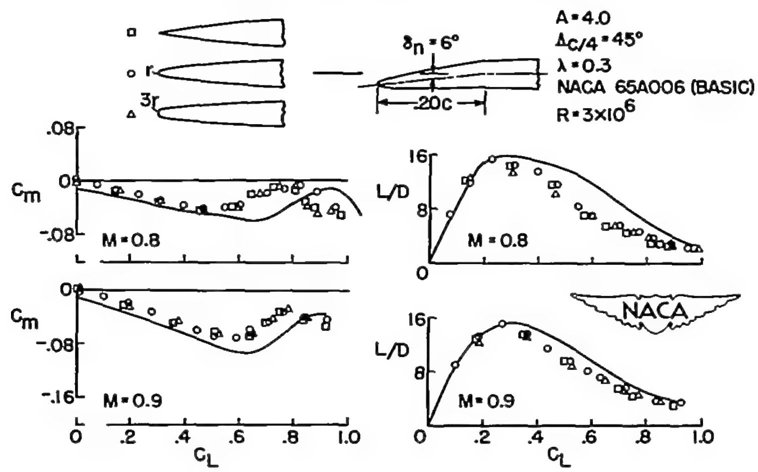

Figure 5

EFFECT OF MODIFICATIONS IN COMBINATION

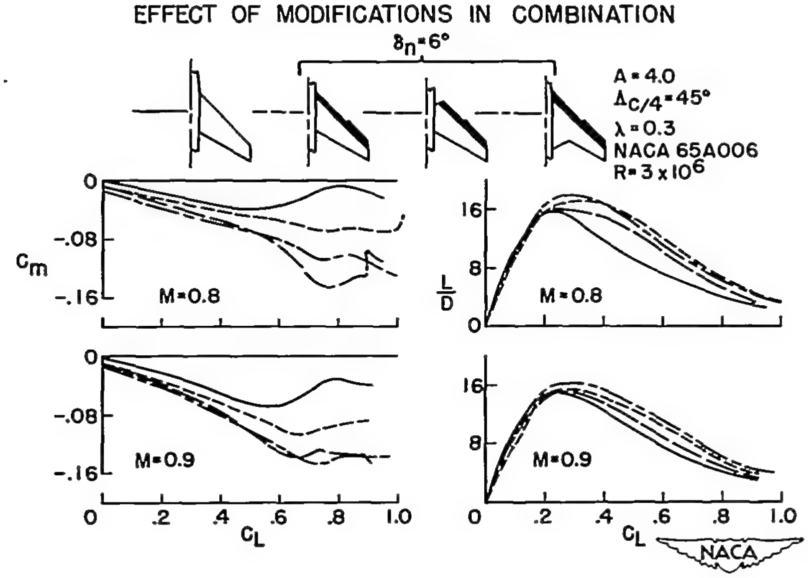

Figure 6

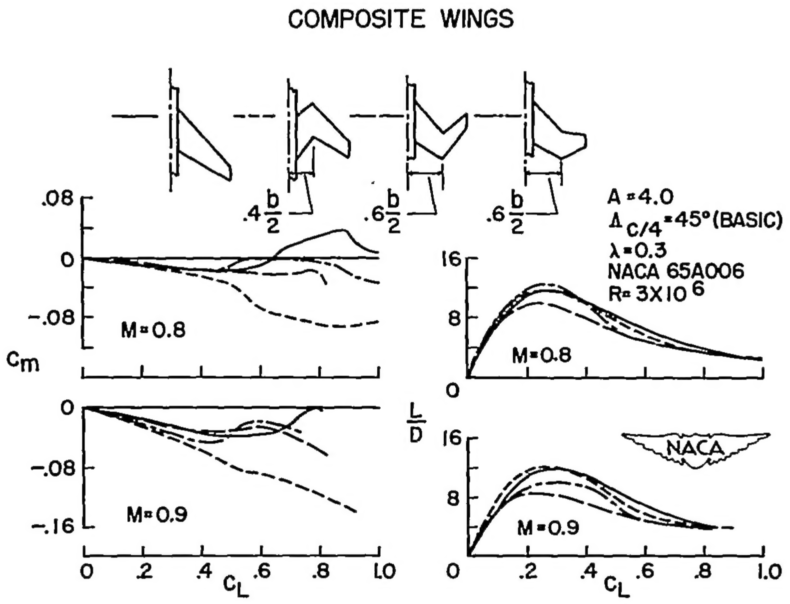

Figure 7

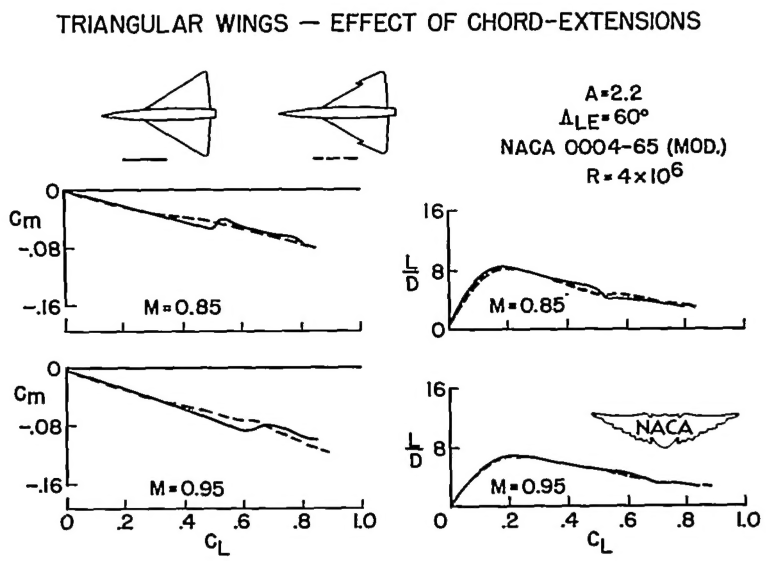

Figure 8

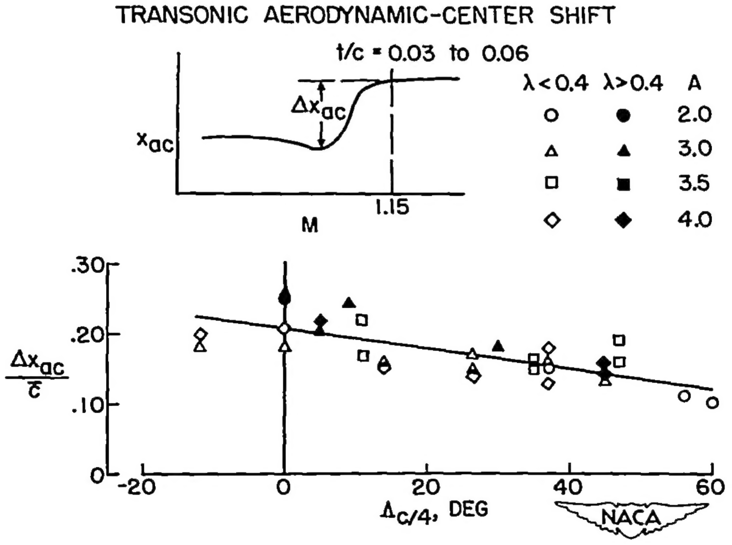

Figure 9

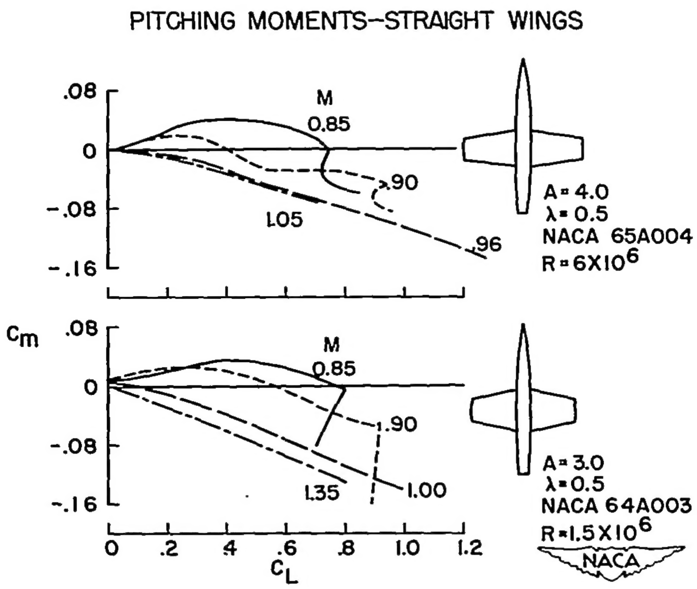

Figure 10

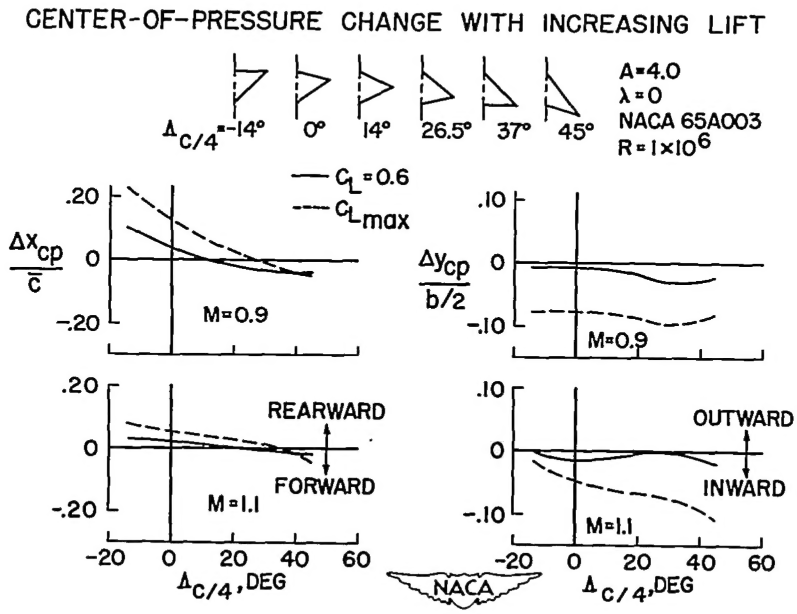

Figure 11

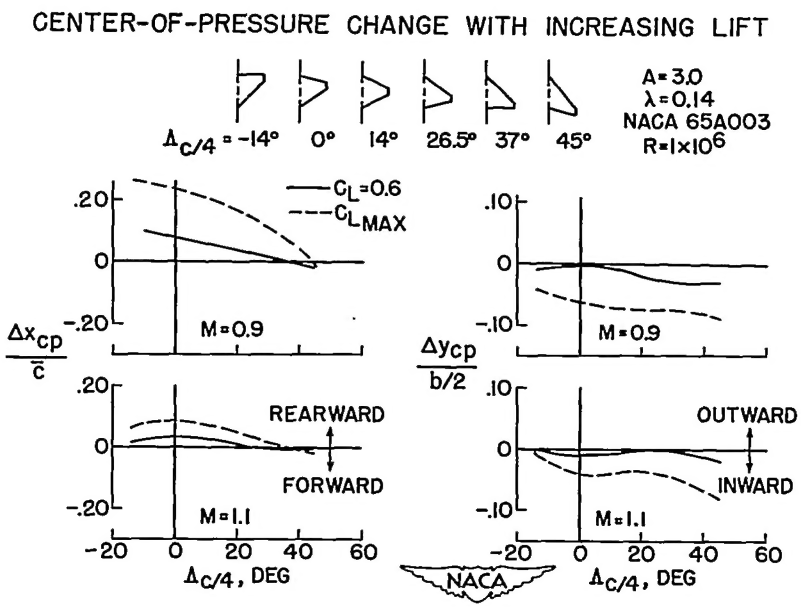

Figure 12

PITCHING MOMENTS — INTERMEDIATE SWEEP

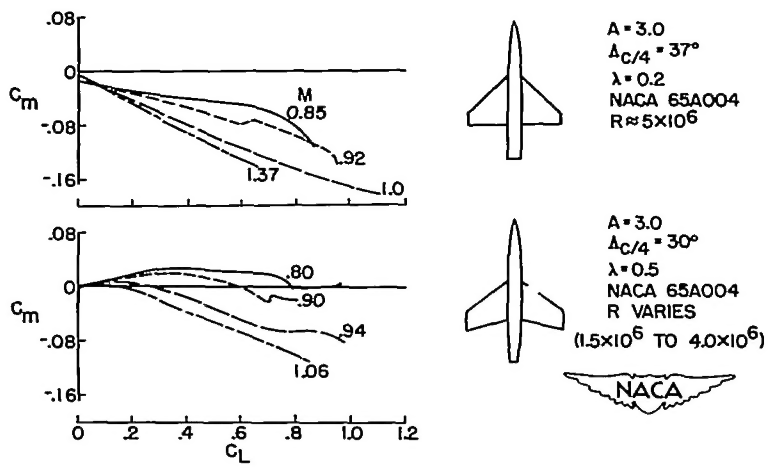

Figure 13

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